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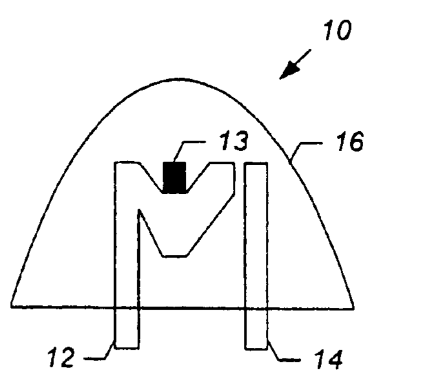
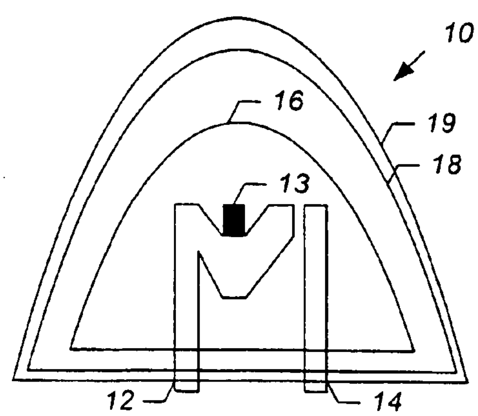
(54) Title: LIGHT-EMITTING DEVICES HAVING MULTIPLE ENCAPSULATION LAYERS WITH AT LEAST ONE OF THE ENCAPSULATION LAYERS INCLUDING NANOPARTICLES AND METHODS OF FORMING THE SAME





(57) Abstract: A light-emitting device includes an active region that is configured to emit light responsive to a voltage applied thereto. A first encapsulation layer at least partially encapsulates the active region and includes a matrix material and nanoparticles, which modify at least one physical property of the first encapsulation layer. A second encapsulation layer at least partially encapsulates the first encapsulation layer.

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LIGHT-EMITTING DEVICES HAVING MULTIPLE ENCAPSULATION LAYERS WITH AT LEAST ONE OF THE ENCAPSULATION LAYERS INCLUDING NANOPARTICLES AND METHODS OF FORMING THE SAME

Field of the Invention

The present invention relates generally to microelectronic devices and fabrication methods therefor, and, more particularly, to light-emitting devices and fabrication methods therefor.

Background of the Invention

Light-emitting diodes (LEDs) are widely used in consumer and commercial applications. As is well known to those skilled in the art, a light-emitting diode generally includes an active region on a microelectronic substrate. The microelectronic substrate may comprise, for example, gallium arsenide, gallium phosphide, alloys thereof, silicon carbide, and/or sapphire. Continued developments in LEDs have resulted in highly efficient and mechanically robust light sources that can cover the visible spectrum and beyond. These attributes, coupled with the potentially long service life of solid state devices, may enable a variety of new display applications, and may place LEDs in a position to compete with well entrenched incandescent and/or fluorescent lamps.

Standard LED packaging typically comprises an epoxy-based encapsulation layer to both protect the active device from the elements and to enhance the optical output of the LED dice. Unfortunately, an epoxy-based encapsulation layer may optically degrade when used with relatively short wavelength (*e.g.*, 525 nm), high flux LEDs.

Summary of the Invention

According to some embodiments of the present invention, a light-emitting device includes an active region that is configured to emit light responsive to a voltage applied thereto. A first encapsulation layer at least partially encapsulates the active region and includes a matrix material and nanoparticles, which modify at least one physical property of the first encapsulation layer. A second encapsulation layer at least partially encapsulates the first encapsulation layer.

In other embodiments of the present invention, the matrix material comprises silicone, a silicone compound, an optical gel, epoxy resin, glass, sol-gel, aerogel, and/or an optically stable polymer.

In still other embodiments of the present invention, the first encapsulation layer is substantially transparent.

In still other embodiments of the present invention, the nanoparticles comprise TiO_2, diamond, silicon carbide, scattering particles, fillers, phosphors, and/or light conversion materials.

In still other embodiments of the present invention, the at least one physical property comprises index of refraction, thermal conductivity, mechanical strength, abrasion resistance, and/or optical stability.

In further embodiments of the present invention, the matrix material is a first matrix material, and the nanoparticles are first nanoparticles. The second encapsulation layer comprises a second matrix material and second nanoparticles that modify at least one physical property of the second encapsulation layer.

In still further embodiments of the present invention, the second matrix material comprises silicone, a silicone compound, an optical gel, epoxy resin, glass, sol-gel, aerogel, and/or an optically stable polymer.

In still further embodiments of the present invention, the second encapsulation layer is substantially transparent.

In still further embodiments of the present invention, the second nanoparticles comprise TiO_2, diamond, silicon carbide, scattering particles, fillers, phosphors, and/or light conversion materials.

In still further embodiments of the present invention, the at least one physical property of the second encapsulation layer comprises index of refraction, thermal conductivity, mechanical strength, abrasion resistance, and/or optical stability.

In still further embodiments of the present invention, an outer surface of the first encapsulation layer, opposite the active region, may be shaped so that light rays from the active region are not incident on the first encapsulation layer at an angle that is greater than a critical angle.

Although described primarily above with respect to device embodiments of the present invention, it will be understood that the present invention may also be embodied as fabrication methods of forming light-emitting devices.

Brief Description of the Drawings

Other features of the present invention will be more readily understood from the following detailed description of specific embodiments thereof when read in conjunction with the accompanying drawings, in which:

FIGS. 1A - 1B are cross-sectional diagrams that illustrate light-emitting devices and fabrication methods therefor, in accordance with some embodiments of the present invention;

FIGS. 2A - 2C are cross-sectional diagrams that illustrate light-emitting devices and fabrication methods therefor, in accordance with additional embodiments of the present invention; and

FIGS. 3A - 3D are cross-sectional diagrams that illustrate light-emitting devices and fabrication methods therefor, in accordance with additional embodiments of the present invention.

Detailed Description of Preferred Embodiments

While the invention is susceptible to various modifications and alternative forms, specific embodiments thereof are shown by way of example in the drawings and will herein be described in detail. It should be understood, however, that there is no intent to limit the invention to the particular forms disclosed, but on the contrary, the invention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the claims. Like numbers refer to like elements throughout the description of the figures. In the figures, the dimensions

of layers and regions are exaggerated for clarity. Each embodiment described herein also includes its complementary conductivity type embodiment.

It will be understood that when an element such as a layer, region or substrate is referred to as being "on" another element, it can be directly on the other element or intervening elements may also be present. It will be understood that if part of an element, such as a surface, is referred to as "inner," it is farther from the outside of the device than other parts of the element. Furthermore, relative terms such as "beneath" or "overlies" may be used herein to describe a relationship of one layer or region to another layer or region relative to a substrate or base layer as illustrated in the figures. It will be understood that these terms are intended to encompass different orientations of the device in addition to the orientation depicted in the figures. Finally, the term "directly" means that there are no intervening elements. As used herein, the term "and/or" includes any and all combinations of one or more of the associated listed items.

It will be understood that, although the terms first, second, etc. may be used herein to describe various elements, components, regions, layers and/or sections, these elements, components, regions, layers and/or sections should not be limited by these terms. These terms are only used to distinguish one element, component, region, layer or section from another region, layer or section. Thus, a first region, layer or section discussed below could be termed a second region, layer or section, and, similarly, a second without departing from the teachings of the present invention.

Embodiments of the present invention will now be described, generally, with reference to GaN-based light-emitting diodes (LEDs) on SiC-based or sapphire (Al_2O_3)-based substrates. The present invention, however, is not limited to such structures. Examples of light-emitting devices that may be used in embodiments of the present invention include, but are not limited to, LEDs and/or laser diodes, such as devices manufactured and sold by Cree, Inc. of Durham, North Carolina. For example, the present invention may be suitable for use with LEDs and/or lasers as described in United States Patent Nos. 6,201,262, 6,187,606, 6,120,600, 5,912,477, 5,739,554, 5,631,190, 5,604,135, 5,523,589, 5,416,342, 5,393,993, 5,338,944, 5,210,051, 5,027,168, 5,027,168, 4,966,862 and/or 4,918,497, the disclosures of which are incorporated herein by reference as if set forth fully herein. Other suitable LEDs and/or lasers are described in United States Patent Application Serial No.

10/140,796, entitled "GROUP III NITRIDE BASED LIGHT EMITTING DIODE STRUCTURES WITH A QUANTUM WELL AND SUPERLATTICE, GROUP III NITRIDE BASED QUANTUM WELL STRUCTURES AND GROUP III NITRIDE BASED SUPERLATTICE STRUCTURES", filed May 7, 2002, as well as United States Patent Application Serial No. 10/057,821, filed January 25, 2002 entitled "LIGHT EMITTING DIODES INCLUDING SUBSTRATE MODIFICATIONS FOR LIGHT EXTRACTION AND MANUFACTURING METHODS THEREFOR" the disclosures of which are incorporated herein as if set forth fully. Furthermore, phosphor coated LEDs, such as those described in United States Patent Application Serial No. 10/659,241 entitled "PHOSPHOR-COATED LIGHT EMITTING DIODES INCLUDING TAPERED SIDEWALLS, AND FABRICATION METHODS THEREFOR," filed September 9, 2003, the disclosure of which is incorporated by reference herein as if set forth full, may also be suitable for use in embodiments of the present invention.

The LEDs and/or lasers may be configured to operate in a "flip-chip" configuration such that light emission occurs through the substrate. In such embodiments, the substrate may be patterned so as to enhance light output of the devices as is described, for example, in United States Patent Application Serial No. 10/057,821, filed January 25, 2002 entitled "LIGHT EMITTING DIODES INCLUDING SUBSTRATE MODIFICATIONS FOR LIGHT EXTRACTION AND MANUFACTURING METHODS THEREFOR" the disclosure of which is incorporated herein by reference as if set forth fully herein.

FIGS. 1A - 1B are cross-sectional diagrams that illustrate light-emitting devices and fabrication methods therefor, in accordance with some embodiments of the present invention. Referring now to **FIG. 1A**, a light-emitting device **10**, in accordance with some embodiments of the present invention, includes an LED, which includes an anode terminal **12**, an active region **13**, such as a diode region, and a cathode terminal **14**, which are electrically coupled to one another. The active region **13** is configured to emit light responsive to a voltage applied thereto via, for example, the anode and cathode terminals **12** and **14**. The light-emitting device **10** further includes a first encapsulation layer **16**, which includes, for example, a matrix material and nanoparticles that modify at least one physical property, such as, for example, index of refraction, thermal conductivity, mechanical strength, abrasion resistance,

and/or optical stability of the first encapsulation layer **16**. The first encapsulation layer **16** at least partially encapsulates the active region in accordance with some embodiments of the present invention and may be substantially transparent. In accordance with various embodiments of the present invention, the matrix material may comprise silicone, a silicone compound, an optical gel, epoxy resin, glass, sol-gel, aerogel, and/or an optically stable polymer. Advantageously, the silicone gel is generally optically stable when exposed to relatively high flux, short wavelength light (*e.g.*, on the order of 525 nm). The nanoparticles in the first encapsulation layer **16** may comprise TiO_2, diamond, silicon carbide, scattering particles, fillers, phosphors, and/or light conversion materials. Thus, for example, the first encapsulation layer **16** may comprise a silicone gel having TiO_2 nanoparticles contained therein. The TiO_2 nanoparticles contained in the silicone gel may increase the index of refraction of the first encapsulation layer **16** to allow the index of refraction of the first encapsulation layer **16** to more closely match the index of refraction of the active region **13** thereby improving light extraction from the active region **13**.

When light travels from one medium to another, it may be refracted such that the angle of refraction is governed by Snell's law as follows: $n_1 \sin\theta_1 = n_2 \sin\theta_2$, where n_1 is the index of refraction for medium 1 and n_2 is the index of refraction for medium 2. The light that escapes, however, has an angular dependence that is less than the "critical angle," which is defined as follows $\theta_{1critical} = \sin^{-1}(n_2/n_1)$. Light that is incident at an angle greater than the critical angle does not pass through to medium 2, but is instead reflected back into medium 1. This reflection is commonly called total internal reflection. To further improve light extraction from the first encapsulation layer **16**, an outer surface of the first encapsulation layer **16**, opposite the active region **13**, may be shaped so that light rays from the active region **13** are not incident on the first encapsulation layer **16** at an angle that is greater than the critical angle, in accordance with some embodiments of the present invention.

Referring now to **FIG. 1B**, the first encapsulation layer **16** is at least partially encapsulated with a second encapsulation layer **18**, which may comprise a second matrix material and second nanoparticles that modify at least one physical property, such as, for example, index of refraction, thermal conductivity, mechanical strength, abrasion resistance, and/or optical stability of the second encapsulation layer **18**. The

second encapsulation layer **18** and may be substantially transparent. In accordance with various embodiments of the present invention, the second matrix material may comprise silicone, a silicone compound, an optical gel, epoxy resin, glass, sol-gel, aerogel, and/or an optically stable polymer. The second nanoparticles may comprise TiO_2, diamond, silicon carbide, scattering particles, fillers, phosphors, and/or light conversion materials.

In particular embodiments of the present invention, the second encapsulation layer **18** may include epoxy, plastic, and/or glass to add rigidity to the packaging of the light-emitting device **10**. To improve the thermal characteristics of the packaging, a third encapsulation layer **19**, which may be substantially transparent, may be used to at least partially encapsulate the second encapsulation layer **18** in accordance with some embodiments of the present invention. The third encapsulation layer **19** may include a thermally conductive material. In accordance with particular embodiments of the present invention, the first, second, and third encapsulation layers **16**, **18**, and **19** may be formed using a casting process.

FIGS. 2A - 2C are cross-sectional diagrams that illustrate light-emitting devices and fabrication methods therefor, in accordance with further embodiments of the present invention. Referring now to **FIG. 2A**, a light-emitting device **20**, in accordance with some embodiments of the present invention, includes an LED, which includes an anode terminal **22**, an active region **23**, such as a diode region, and a cathode terminal **24**, which are electrically coupled to one another. The active region **23** is configured to emit light responsive to a voltage applied thereto via, for example, the anode and cathode terminals **22** and **24**. The light-emitting device **20** further includes a first encapsulation layer **26**, which includes, for example, a matrix material and nanoparticles that modify at least one physical property, such as, for example, index of refraction, thermal conductivity, mechanical strength, abrasion resistance, and/or optical stability of the first encapsulation layer **26**. The first encapsulation layer **26** at least partially encapsulates the active region in accordance with some embodiments of the present invention and may be substantially transparent. In accordance with various embodiments of the present invention, the matrix material may comprise silicone, a silicone compound, an optical gel, epoxy resin, glass, sol-gel, aerogel, and/or an optically stable polymer. The nanoparticles in the first

encapsulation layer 26 may comprise TiO_2, diamond, silicon carbide, scattering particles, fillers, phosphors, and/or light conversion materials. Thus, for example, the first encapsulation layer **26** may comprise silicone gel, epoxy, and/or a polymer having TiO_2 nanoparticles contained therein. The TiO_2 nanoparticles contained in the matrix material may increase the index of refraction of the first encapsulation layer **26** to allow the index of refraction of the first encapsulation layer **26** to more closely match the index of refraction of the active region **23** thereby improving light extraction from the active region **23**.

To further improve light extraction from the first encapsulation layer **26**, an outer surface of the first encapsulation layer **26**, opposite the active region **23**, may be shaped so that light rays from the active region **23** are not incident on the first encapsulation layer **26** at an angle that is greater than the critical angle, in accordance with some embodiments of the present invention. In addition, the first encapsulation layer **26** may further include phosphor particles, to fabricate, for example, a white LED lamp, in accordance with some embodiments of the present invention. In accordance with particular embodiments of the present invention, the first encapsulation layer **26** may be formed using a casting or dispensing process.

Referring now to **FIG. 2B**, the light-emitting device **20** further comprises a second encapsulation layer **27** that at least partially encapsulates the first encapsulation layer **26** and may be substantially transparent. The second encapsulation layer **27** may comprise a second matrix material and second nanoparticles that modify at least one physical property, such as, for example, index of refraction, thermal conductivity, mechanical strength, abrasion resistance, and/or optical stability of the second encapsulation layer **27**. In accordance with various embodiments of the present invention, the second matrix material may comprise silicone, a silicone compound, an optical gel, epoxy resin, glass, sol-gel, aerogel, and/or an optically stable polymer. The second nanoparticles may comprise TiO_2, diamond, silicon carbide, scattering particles, fillers, phosphors, and/or light conversion materials. Thus, in particular embodiments of the present invention, the second encapsulation layer **27** may comprise silicone gel.

Referring now to **FIG. 2C**, the second encapsulation layer **27** is at least partially encapsulated with a third encapsulation layer **28**, which may be substantially

transparent and may comprise a third matrix material and third nanoparticles that modify at least one physical property, such as, for example, index of refraction, thermal conductivity, mechanical strength, abrasion resistance, and/or optical stability of the third encapsulation layer **28**. In accordance with various embodiments of the present invention, the third matrix material may comprise silicone, a silicone compound, an optical gel, epoxy resin, glass, sol-gel, aerogel, and/or an optically stable polymer. The third nanoparticles may comprise TiO_2, diamond, silicon carbide, scattering particles, fillers, phosphors, and/or light conversion materials.

In particular embodiments of the present invention, the third encapsulation layer **28** may include epoxy, plastic, and/or glass to add rigidity to the packaging of the light-emitting device **20**. To improve the thermal characteristics of the packaging, a fourth encapsulation layer **29** may be used to at least partially encapsulate the third encapsulation layer **28** in accordance with some embodiments of the present invention. The fourth encapsulation layer **29** may include a thermally conductive material and may be substantially transparent. In accordance with particular embodiments of the present invention, the second, third, and fourth encapsulation layers **27**, **28**, and **29** may be formed using a casting process.

FIGS. 3A - 3D are cross-sectional diagrams that illustrate light-emitting devices and fabrication methods therefor, in accordance with some other embodiments of the present invention. Referring now to **FIG. 3A**, a light-emitting device **30**, in accordance with some embodiments of the present invention, includes an LED, which includes an anode terminal **32**, an active region **33**, such as a diode region, and a cathode terminal **34**, which are electrically coupled to one another. The active region **33** is configured to emit light responsive to a voltage applied thereto via, for example, the anode and cathode terminals **32** and **34**. The light-emitting device **30** further includes a first encapsulation layer **35**, which includes, for example, a matrix material and nanoparticles that modify at least one physical property, such as, for example, index of refraction, thermal conductivity, mechanical strength, abrasion resistance, and/or optical stability of the first encapsulation layer **35**. The first encapsulation layer **35** at least partially encapsulates the active region and may be substantially transparent in accordance with some embodiments of the present invention. In accordance with various embodiments of the present invention, the matrix material may comprise silicone, a silicone compound, an optical gel, epoxy resin, glass, sol-

gel, aerogel, and/or an optically stable polymer. The nanoparticles in the first encapsulation layer 35 may comprise TiO_2, diamond, silicon carbide, scattering particles, fillers, phosphors, and/or light conversion materials. Thus, for example, the first encapsulation layer **35** may comprise silicone gel, epoxy, and/or a polymer having TiO_2 nanoparticles contained therein. The TiO_2 nanoparticles contained in the matrix material may increase the index of refraction of the first encapsulation layer **36** to allow the index of refraction of the first encapsulation layer **35** to more closely match the index of refraction of the active region **35** thereby improving light extraction from the active region **33**.

To further improve light extraction from the first encapsulation layer **35**, an outer surface of the first encapsulation layer **35**, opposite the active region **33**, may be shaped so that light rays from the active region **33** are not incident on the first encapsulation layer **35** at an angle that is greater than the critical angle, in accordance with some embodiments of the present invention.

Referring now to **FIG. 3B**, the light-emitting device **30** further comprises a second encapsulation layer **36** that at least partially encapsulates the first encapsulation layer **35** and may be substantially transparent. The second encapsulation layer **36** may comprise a second matrix material and second nanoparticles that modify at least one physical property, such as, for example, index of refraction, thermal conductivity, mechanical strength, abrasion resistance, and/or optical stability of the second encapsulation layer **36**. In accordance with various embodiments of the present invention, the second matrix material may comprise silicone, a silicone compound, an optical gel, epoxy resin, glass, sol-gel, aerogel, and/or an optically stable polymer. The second nanoparticles may comprise TiO_2, diamond, silicon carbide, scattering particles, fillers, phosphors, and/or light conversion materials. Thus, in particular embodiments of the present invention, the second encapsulation layer **36** may comprise silicone gel, epoxy, and/or a polymer having phosphor particles contained therein to fabricate, for example, a white LED lamp, in accordance with some embodiments of the present invention. In addition, the second encapsulation layer **36** may further include TiO_2 nanoparticles in accordance with some embodiments of the present invention. Advantageously, by separating the second encapsulation layer **36** from the active region **33**, increased light output may be

obtained from the light-emitting device. In accordance with particular embodiments of the present invention, the first and second encapsulation layers **35** and **36** may be formed using a casting or dispensing process.

Referring now to **FIG. 3C**, the light-emitting device **30** further comprises a third encapsulation layer **37**, that at least partially encapsulates the second encapsulation layer **36** and may be substantially transparent. The third encapsulation layer **37** may comprise a third matrix material and third nanoparticles that modify at least one physical property, such as, for example, index of refraction, thermal conductivity, mechanical strength, abrasion resistance, and/or optical stability of the third encapsulation layer **37**. In accordance with various embodiments of the present invention, the third matrix material may comprise silicone, a silicone compound, an optical gel, epoxy resin, glass, sol-gel, aerogel, and/or an optically stable polymer. The third nanoparticles may comprise TiO_2, diamond, silicon carbide, scattering particles, fillers, phosphors, and/or light conversion materials. Thus, in particular embodiments of the present invention, the third encapsulation layer **37** may comprise silicone gel.

Referring now to **FIG. 3D**, the third encapsulation layer **37** is at least partially encapsulated with a fourth encapsulation layer **38**, which may be substantially transparent and may comprise a fourth matrix material and fourth nanoparticles that modify at least one physical property, such as, for example, index of refraction, thermal conductivity, mechanical strength, abrasion resistance, and/or optical stability of the fourth encapsulation layer **38**. In accordance with various embodiments of the present invention, the fourth matrix material may comprise silicone, a silicone compound, an optical gel, epoxy resin, glass, sol-gel, aerogel, and/or an optically stable polymer. The fourth nanoparticles may comprise TiO_2, diamond, silicon carbide, scattering particles, fillers, phosphors, and/or light conversion materials.

In particular embodiments of the present invention, the fourth encapsulation layer **38** may include epoxy, plastic, and/or glass to add rigidity to the packaging of the light-emitting device **30**. To improve the thermal characteristics of the packaging, a fifth encapsulation layer **39** may be used to at least partially encapsulate the fourth encapsulation layer **38** in accordance with some embodiments of the present invention. The fifth encapsulation layer **39** may include a thermally conductive material and may be substantially transparent. In accordance with particular

embodiments of the present invention, the third, fourth, and fifth encapsulation layers **37**, **38**, and **39** may be formed using a casting process.

In general, embodiments of the invention may comprise a sequence of multiple (two or more) encapsulation layers, each either fully or partially encapsulating the previous layers or light-emitting device. Each encapsulation layer may comprise one of a variety of matrix, nanoparticle, additive/filler materials as described above, and each layer may serve a specific complimentary function to improve the performance of the resulting package. It is generally desirable that the encapsulation layers do not substantially absorb light from the light-emitting device. Moreover, the interface between the encapsulation layers may be designed to enhance the optical and/or chemical properties. Compatibility of chemical and other physical properties, such as chemical reactions, adhesion, thermal expansion, etc. may place constraints upon the geometry and/or the configuration of the interface between various encapsulation layers.

In concluding the detailed description, it should be noted that many variations and modifications can be made to the preferred embodiments without substantially departing from the principles of the present invention. All such variations and modifications are intended to be included herein within the scope of the present invention, as set forth in the following claims.

Claims

That which is claimed:

1. A light-emitting device, comprising:

an active region that is configured to emit light responsive to a voltage applied thereto;

a first encapsulation layer that at least partially encapsulates the active region, the first encapsulation layer comprising a matrix material and nanoparticles that modify at least one physical property of the first encapsulation layer; and

a second encapsulation layer that at least partially encapsulates the first encapsulation layer.

2. The light-emitting device of Claim 1, wherein the matrix material comprises silicone, a silicone compound, an optical gel, epoxy resin, glass, sol-gel, aerogel, and/or an optically stable polymer.

3. The light-emitting device of Claim 1, wherein the first encapsulation layer is substantially transparent.

4. The light-emitting device of Claim 1, wherein the nanoparticles comprise TiO_2, diamond, silicon carbide, scattering particles, fillers, phosphors, and/or light conversion materials.

5. The light-emitting device of Claim 1, wherein the at least one physical property comprises index of refraction, thermal conductivity, mechanical strength, abrasion resistance, and/or optical stability.

6. The light-emitting device of Claim 1, wherein the matrix material is a first matrix material, and the nanoparticles are first nanoparticles and wherein the second encapsulation layer comprises a second matrix material and second nanoparticles that modify at least one physical property of the second encapsulation layer.

7. The light-emitting device of Claim 6, wherein the second matrix material comprises silicone, a silicone compound, an optical gel, epoxy resin, glass, sol-gel, aerogel, and/or an optically stable polymer.

8. The light-emitting device of Claim 6, wherein the second encapsulation layer is substantially transparent.

9. The light-emitting device of Claim 6, wherein the second nanoparticles comprise TiO_2, diamond, silicon carbide, scattering particles, fillers, phosphors, and/or light conversion materials.

10. The light-emitting device of Claim 6, wherein the at least one physical property of the second encapsulation layer comprises index of refraction, thermal conductivity, mechanical strength, abrasion resistance, and/or optical stability.

11. The light-emitting device of Claim 1, wherein an outer surface of the first encapsulation layer, opposite the active region, is shaped so that light rays from the active region are not incident on the first encapsulation layer at an angle that is greater than a critical angle.

12. A method of forming a light-emitting device, comprising:

forming an active region that is configured to emit light responsive to a voltage applied thereto;

forming a first encapsulation layer that at least partially encapsulates the active region, the first encapsulation layer comprising a matrix material and nanoparticles that modify at least one physical property of the first encapsulation layer; and

forming a second encapsulation layer that at least partially encapsulates the first encapsulation layer.

13. The method of Claim 12, wherein the matrix material comprises silicone, a silicone compound, an optical gel, epoxy resin, glass, sol-gel, aerogel, and/or an optically stable polymer.

14. The method of Claim 12, wherein the first encapsulation layer is substantially transparent.

15. The method of Claim 12, wherein the nanoparticles comprise TiO_2, diamond, silicon carbide, scattering particles, fillers, phosphors, and/or light conversion materials.

16. The method of Claim 12, wherein the at least one physical property comprises index of refraction, thermal conductivity, mechanical strength, abrasion resistance, and/or optical stability.

17. The method of Claim 12, wherein the matrix material is a first matrix material, and the nanoparticles are first nanoparticles and wherein the second encapsulation layer comprises a second matrix material and second nanoparticles that modify at least one physical property of the second encapsulation layer.

18. The method of Claim 17, wherein the second matrix material comprises silicone, a silicone compound, an optical gel, epoxy resin, glass, sol-gel, aerogel, and/or an optically stable polymer.

19. The method of Claim 17, wherein the second encapsulation layer is substantially transparent.

20. The method of Claim 17, wherein the second nanoparticles comprise TiO_2, diamond, silicon carbide, scattering particles, fillers, phosphors, and/or light conversion materials.

21. The method of Claim 17, wherein the at least one physical property of the second encapsulation layer comprises index of refraction, thermal conductivity, mechanical strength, abrasion resistance, and/or optical stability.

22. The method of Claim 12, wherein an outer surface of the first encapsulation layer, opposite the active region, is shaped so that light rays from the

active region are not incident on the first encapsulation layer at an angle that is greater than a critical angle.

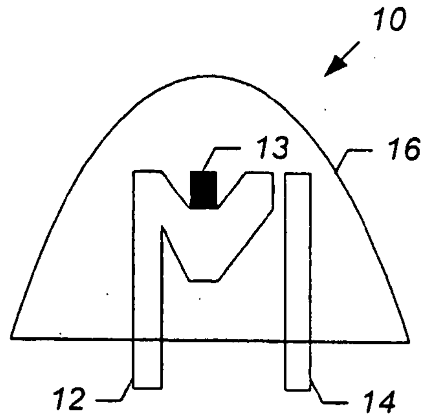

FIG. 1A

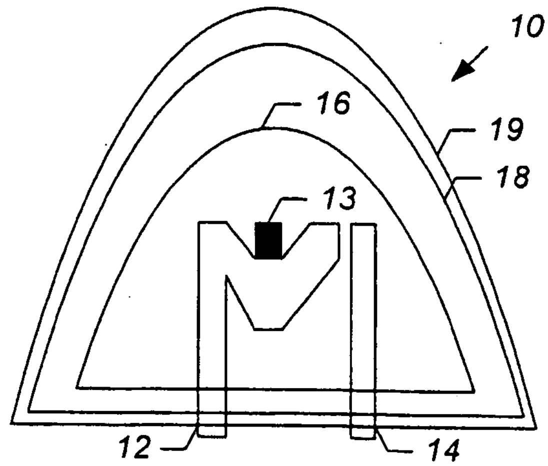

FIG. 1B

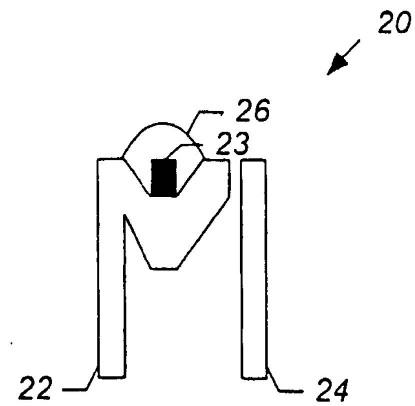

FIG. 2A

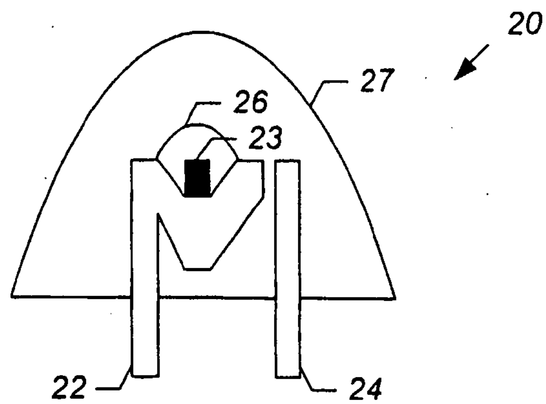

FIG. 2B

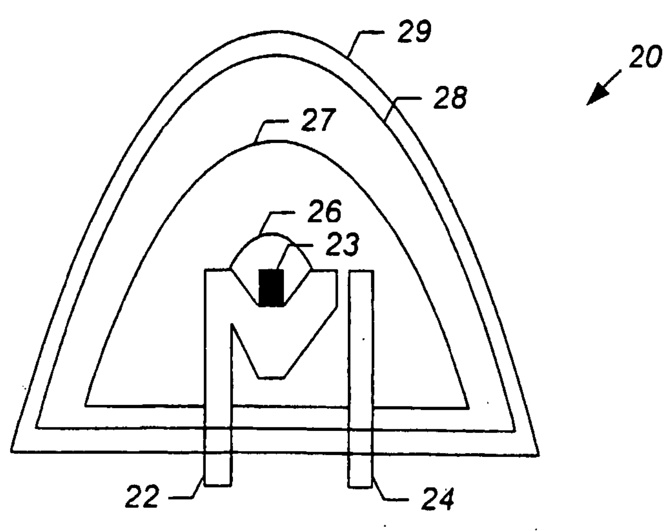

FIG. 2C

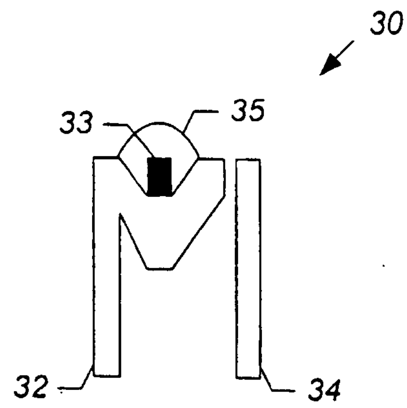

FIG. 3A

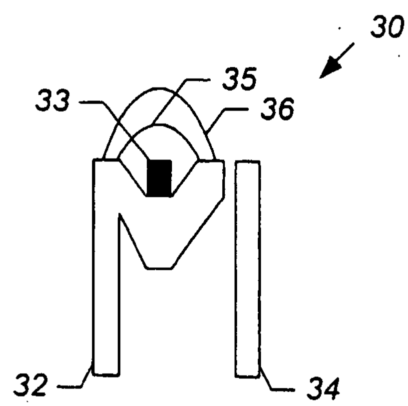

FIG. 3B

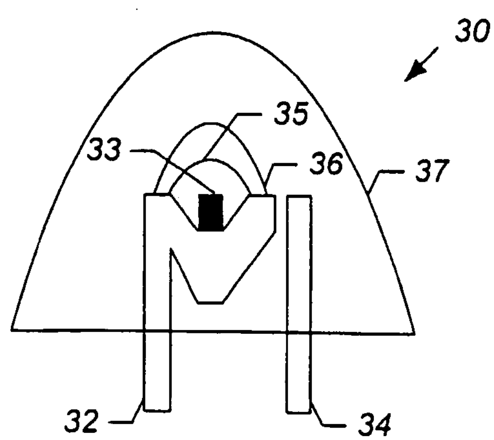

FIG. 3C

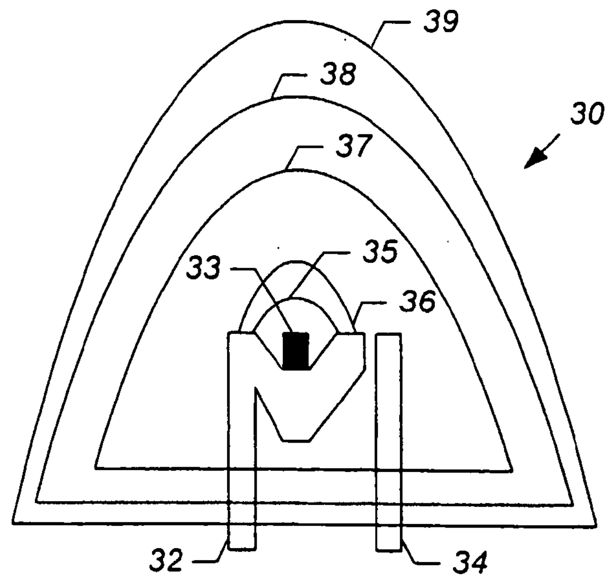

FIG. 3D

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US2005/011592

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H05B33/04

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H05B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, COMPENDEX, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2003/122482 A1 (YAMANAKA OSAMU ET AL) 3 July 2003 (2003-07-03) pages 1-4,6-7; claims	1-22
X	US 2004/004434 A1 (NISHI TAKESHI ET AL) 8 January 2004 (2004-01-08) pages 1-6,8	1-22
X	US 2003/117068 A1 (FORREST STEPHEN ET AL) 26 June 2003 (2003-06-26) the whole document	1-22
A	EP 0 961 525 A (SEIKO EPSON CORPORATION) 1 December 1999 (1999-12-01) columns 4,8; claims	1-22

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
12 August 2005	23/08/2005

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Doslik, N

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 99/03087 A (FED CORPORATION; HELLER, CHRISTIAN, M; JONES, GARY, W) 21 January 1999 (1999-01-21) pages 5,7	1-22

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